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6. AUTHOR(S)
Miyo Yokota, Larry G. Berglund, Julio A. Gonzalez and Laurie A. Blanchard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Biophysics and Biomedical Modeling Division
U.S. Army Research Institute of Environmental Medicine
Building 42 - Kansas Street
Natick, MA 01760

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This study demonstrates a method for monitoring evaporative sweat rates (EvapSR) during steady and intermittent activities. The method was validated on a sweating thermal manikin wearing a long sleeved shirt and trousers (standard military battle dress uniform) instrumented with temperature-humidity sensors under the clothing. The manikin tests were at steady state conditions in an environmental chamber at 35°C/50%RH and wind speed ranging between 0.36 and 1.94 $m \cdot s^{-1}$. The manikin was adjusted to produce sweat rates between 0 and 150 $g \cdot m^{-2} \cdot h^{-1}$. EvapSR was estimated from weighted measured skin wettedness and the maximum evaporative rate, and compared to the manikin's sweat rate. This technique was further validated with humans engaged in intermittent work. Overall, this is a simple promising approach for estimating EvapSR. The method is non-invasive and enables monitoring and assessment for safety, health and hydration status of industrial and military personnel engaged in a wide range of situations.

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Transient Sweat Rate Calculation from Humidity Measurements under Clothing

M. Yokota, L.G. Berglund*, J.A. Gonzalez, L.A. Blanchard
U.S. Army Research Institute of Environmental Medicine (USARIEM), Natick, MA USA
* corresponding author: larry.berglund@us.army.mil

Abstract

This study demonstrates a method for monitoring evaporative sweat rates (EvapSR) during steady and intermittent activities. The method was validated on a sweating thermal manikin wearing a long sleeved shirt and trousers (standard military battle dress uniform) instrumented with temperature-humidity sensors under the clothing. The manikin tests were at steady state conditions in an environmental chamber at 35°C/50%RH and wind speed ranging between 0.36 and 1.94 m•s^{-1}. The manikin was adjusted to produce sweat rates between 0 and 150 g•m^{-2}• h^{-1}. EvapSR was estimated from weighted measured skin wettedness and the maximum evaporative rate, and compared to the manikin's sweat rate. This technique was further validated with humans engaged in intermittent work. Overall, this is a simple promising approach for estimating EvapSR. The method is non-invasive and enables monitoring and assessment for safety, health and hydration status of industrial and military personnel engaged in a wide range of situations.

1. Introduction

When thermoregulatory mechanisms cannot wholly compensate for prolonged exposure to heat stress, the physiological consequences may be severe water loss from blood plasma, an increase in heart rate for skin blood flow to maintain blood pressure, and an increase in core temperature. Non-compensable heat stress decreases productivity and endurance of performance, and may eventually cause heat related illness (e.g., dehydration, fatigue, heat stroke) [1]. The evaporation of

sweat from the body surface is the most important thermoregulatory mechanism for dispersing excess heat from the body. Evaporation of sweat from the skin lowers core and skin temperatures, thus better enabling proper body temperatures in the heat. However, workers (e.g., firefighters, military personnel, mining industries) exposed to uncompensated hot environmental and/or strenuous operational conditions can sweat up to 2 L•h^{-1} for several hours[1]. To sustain the sweating rate (SR), adequate hydration levels must be maintained by replacing water lost during activities in warm and hot conditions. The majority of current training and fluid replacement guidelines for heat strain prevention were primarily developed from a single element, such as air temperature, or the combinations of clothing, activity levels, and/or air temperatures[7,10]. Despite these guidelines, heat related injuries and illness in both civilian and military workplaces are still serious challenges[4,14]. In part, the guidance was established only for working and environment conditions which are covered by standard water tables. Other factors, such as levels of heat acclimation, work duration and cycles, gender, or ethnicity may create additional differences in SR. Thus, to ensure individual workers' safety, health, and performance in warm and hot environments, the capability to monitor and estimate the accurate water loss (WL), and the consequent requirement for water replacement, is important.

A traditional approach to quantify WL for predicting water requirement is to calculate the difference in body weight and associated weights (e.g., clothing, respiration, urine) before and after work[11,12]. However, particularly for workers required to perform their duties for long hours under various operational and environmental stresses, this approach to assess WL can be inconvenient. As an alternative to repetitive weighing, evaporative sweat rate (EvapSR) can be continuously monitored and estimated from humidity measurements made with compact sensors placed under clothing. In this way, the individual's SR that may be altered or controlled by different elements (e.g., clothing, work levels and cycles, durations, acclimation status) can be easily assessed. In addition, EvapSR calculations and monitoring provide guidance for operational, environmental and other factors which are not covered by standard water tables. These SR sensors enable investigators to identify critical times when individual workers require water to compensate for heat stress. This study made use of a sweating manikin and data from human studies to investigate the accuracy and dynamic response of SR calculated by the transient clothing method (TCM). The method depends on the humidity gradient across clothing fabrics and their evaporation properties to estimate EvapSR over an extended period of time.

2. Methodology

A sweating manikin was instrumented with five relative humidity (RH) and temperature sensors (RHU-600A-ARM, ShinYei Kaisha, Kobe, Japan) distributed uniformly around the front torso region. The manikin, wearing a standard battle dress uniform (intrinsic clo = 0.75), was placed for < 7 h in an environmental

chamber at 35°C/50% RH with wind speeds ranging between 0.36 to 1.94 $m \cdot s^{-1}$. The SR of the manikin was controlled at levels of 0, 50, 100 and 150 $g \cdot m^{-2} \cdot h^{-1}$. EvapSR is estimated from weighted measured skin wettedness (w) and maximum evaporative heat loss rate (E_{max}):

$$EvapSR = w \cdot E_{max}/\lambda \quad [g \cdot m^{-2} \cdot h^{-1}] \qquad [1]$$

where λ is latent heat of evaporation, and w, the fraction of skin covered with water, is defined[5] as a ratio of observed evaporation heat loss rate (E) to E_{max} or:

$$w = E/E_{max} \qquad [2]$$

E_{max} was calculated, assuming completely wet skin (w=1), as:

$$E_{max} = (P_{sk} - P_a)/R_{pclt} \quad [W \cdot m^{-2}] \qquad [3]$$

where P_a is ambient vapour pressure (Torr) and P_{sk} is saturated vapour pressure (Torr) of water at skin temperature. R_{pclt} (Torr) is the total vapour resistance of the clothing from skin to ambient. R_{pclt} was previously measured at various air speeds on the sweating manikin according to ASTM F2370[2]. E is similarly calculated but with actual local average vapour pressure measured under the clothing (P_{uc}) that may be less than P_{sk} because the skin is less covered with water. Substituting E and E_{max} into equation 2 results[3] in:

$$w = (P_{uc} - P_a)/(P_{sk} - P_a) \qquad [4]$$

which can be readily evaluated from the skin temperature and humidity measured under clothing and in the surrounding ambient air. The EvapSR values were compared with the SR of the manikin using a Wilcoxon test due to characteristics of the data distribution and sample size.

Values estimated using TCM were also compared to laboratory measurements from two human studies[6,11]. Unlike the sweating manikin, there are regional differences in SR[8] for human skin. EvapSR was calculated using equation 1 where w is weighted mean skin wettedness of the measured regional w_i values:

$$w = \Sigma(w_i \cdot p_i)/\Sigma p \qquad [5]$$

where $p_i = BSR_i \cdot SRR_i/(\Sigma(BSR \cdot SRR))$, BSR_i = body surface ratio by region, SRR_i = sweat rate distribution ratio corresponding to the region. The weighting factor (p) was determined by the combinations of Kuno's SR distribution ratio (50% from the trunk, 25% from the legs, and the remaining 25%)[8] and Lund-Browder body surface ratio (head and neck for 9% of total BSA, anterior and posterior trunks, 36%; each arm, 9%; each leg, 18%; and 1% represent genitalia and perineum)[9].

For the first human study (HS1), nine human subjects (age: 23 ± 4 [SD] yr, height: 174.2 ± 5.2 cm; weight: 73.4 ± 6.5 kg), exercised 170-min intermittent treadmill walking at 27°C/75% RH with a wind speed of 1.1 m•s^{-1} [11]. The subjects wore hot weather battle dress uniforms (intrinsic clo = 0.70), and RH (IH-3602, Honeywell, International, Freeport, IL) and temperature (FR-025-TH44033-F6, Concept Engineering, Old Saybrook, CT) sensors were placed on back, arm, and thigh under the uniform.

Total WL for HS1 was determined by the difference in body mass, corrected for clothing weight and the SR before and after exercise[11]. A USARIEM human thermal regulatory model, Initial Capability Decision Aid (ICDA) model[15], was utilized to compare the temporal characteristics of WL estimated by TCM with the model's predicted WL. ICDA is a heat stress prediction model, utilizing anthropological characteristics (age, height, weight, clothing) and of a known metabolic level or real time inputs of estimated metabolic activity derived from heart rate and local weather (ambient temperature, RH, wind speed) to make predictions and estimates of physiological responses[15]. In addition, the mean difference in total body WL based on different methods (measured, ICDA, and TCM) was compared using a repeated measures analysis of variance.

For the second human study (HS2), only mean data of six adult male subjects (age: 30 yr; height: 188 cm; weight: 85.2 kg), including weighted skin temperature and w, were available. Humidity sensors were placed on various locations of the skin (upper arm, lower arm, chest, back, thigh calf). Thermocouples measured sensor temperatures at each location (IH-3602C, Honeywell International, Freeport, IL). Subjects, wearing tight fitting100% cotton single layer long sleeved sportswear (top and bottom, intrinsic clo = 0.46) in 12°C/50%RH with still air (0.05 m•s^{-1}), rested for the first 30 min, bicycled ~ 4 MET for 45 min, then rested for 30 min[6]. The horizontal cycle ergometer was placed on top of a sensitive balance to measure the subject's rate of weight loss ($\pm$1g). ICDA was also utilized for comparing model predicted values with measured WL and calculated WL by TCM. For both human studies, the water retained in the clothing was added to SR to calculate the total WL. The respiration loss (Wres) was also added to EvapSR to compare measured WL using the follow equation:

$$Wres = (0.0023 \bullet M \bullet (44 - P_a))/0.068 \qquad [g \bullet m^{-2} \bullet h^{-1}] \qquad [6]$$

where M = work rate (W•m^{-2}) and P_a = ambient vapour pressure (Torr).

3. Results

3.1 Manikin validation
Table 1 is the summary of the predicted SR based on the methodology described in the previous section, together with the measured SR and mean skin w of the manikin for various wind speeds (0.36 – 1.94 m•s^{-1}). When SR is constant, as wind speed

increases w decreases (Experiment A). SR proportionally corresponds to w when wind speed is constant (Experiment B). In both experiments (A and B), the mean estimated EvapSR was not statistically different from the mean SR of the manikin (p > 0.05).

3.2 Human data validation

Figure 1 compares the measured mean (n = 9) for HS1 to WL values estimated using TCM and ICDA models. Overall, WL calculated by TCM showed temporal changes which accurately reflected the pattern of work-rest cycles during the experiment, as did the ICDA predictions, but TCM values were sometimes almost 10% lower than WL predicted by the model. The grand mean WL predicted by ICDA was 3.2 g•min^{-1} which is very close to grand mean measured WL, 3.1 g•min^{-1}. The grand mean WL using TCM was 2.8 g•min^{-1}. Table 2 shows the individual and grand mean data summary of the measured, TCM calculated, and ICDA model predicted WL. The mean difference in WL among different methods was not statistically different (p > 0.05).

	SR $(g \cdot m^{-2} \cdot h^{-1})$	Wind speed $(m \cdot s^{-1})$	Mean w	Estimated SR $(g \cdot m^{-2} \cdot h^{-1})$
Experiment A.				
constant SR	100.0	0.36	0.57	98.3
	100.0	1.15	0.44	116.9
	100.0	1.94	0.18	81.2
	100.0	1.15	0.30	79.4
	100.0	0.36	0.61	106.7
Mean (SD)	100 (0)			96.5 (16.2)
Experiment B.				
constant wind speed	100.0	1.15	0.32	86.8
	150.0	1.15	0.55	148.2
	50.0	1.15	0.18	48.2
	0.0	1.15	0.04	9.6
Mean (SD)	75 (41.7)			73.2 (39.9)

Table 1: A summary of sweat rate (SR) and mean skin wettedness (w) of manikin with various wind speeds (Experiment A), and various manikin SR (Experiment B)
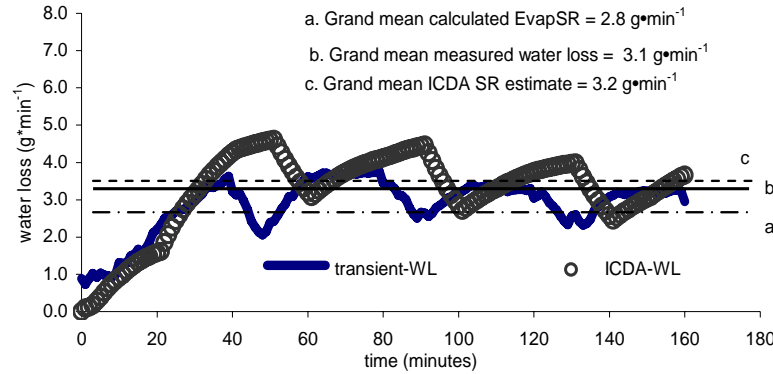
Figure 1 A summary of mean transient water loss (WL) and Initial Capability Decision Aid (ICDA) predicted WL, and measured means for Human Study 1.

Subject	measured WL	ICDA WL	Transient WL
1	3.7	2.3	3.2
2	3.4	4.0	2.2
3	1.6	2.3	2.4
4	3.2	4.3	2.8
5	3.2	2.7	1.6
6	4.0	3.1	2.9
7	2.6	2.8	4.0
8	2.8	3.3	2.9
9	3.7	3.9	3.0
Mean (SD)	3.13 (0.7)	3.20 (0.7)	2.8 (0.7)

Table 2: Summary of comparisons between measured water loss (WL), and WL calculated using Initial Capability Decision Aid (ICDA) model and transient method (TCM) (unit: g•min^{-1}) for Human Study 1.

A comparison of the HS2 mean measured WL and the values estimated using the TCM and ICDA model is presented in Figure 2. Grand means of measured, transient, and ICDA WL were 2.0, 2.4 and 2.8 g•min^{-1}. Overall, the patterns of WL estimated by both TCM and ICDA reflected a rest-exercise-recovery cycle. However, ~5 min time delay in the increases of transient SR after exercise was observed, resulting from the time lag between weight loss measured from the scale and the increase of w[6].
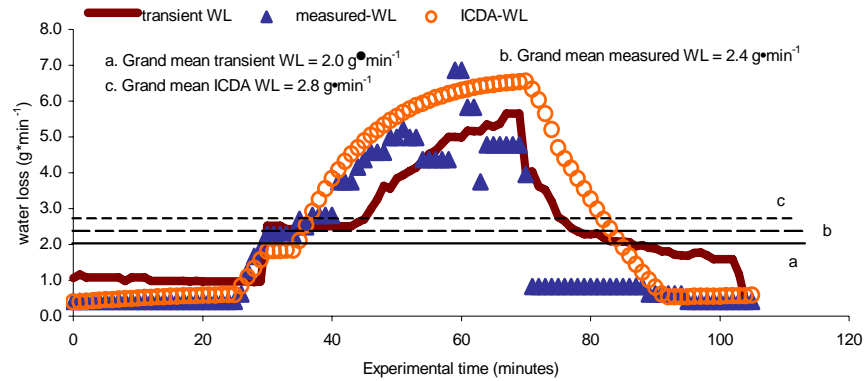
Figure 2 Summary of mean measured, transient, and Initial Capability Decision Aid (ICDA) water loss (WL) in Human Study 2

4. Discussion and Conclusion

The transient method for estimating SR and WL was investigated. The results of the manikin and human experiment showed that this approach is promising. The measured EvapSR of the manikin based on TCM was not statistically different from the mean manikin SR output at constant and variable wind speeds and SRs. Comparisons of measured WL and the estimated WL by TCM using two human studies also demonstrated small mean (0.3 – 0.4 g•min^{-1}) differences. Transient technique calculations in this study captured the different levels of WL during intermittent exercises (HS1, HS2). The values calculated using TCM demonstrated a slight time lag in the onset of increasing sweating relative to values measured by the scale (HS2). This delay appears to be related to sensors and fabric moisture absorption. The most common way to monitor total body WL is by a single (pre-post) measurement of changes in body mass during the activity. In contrast, the continuous subject weighing procedure used in HS2 is only applicable to laboratory applications.

This TCM approach offers the advantage of monitoring temporal WL of workers continuously for long periods of intermittent activity that may also involve changing temperature and humidity conditions. Because variation in WL and SR exists between different populations (e.g., ethnic groups, gender, acclimation status)[13] and within individuals[8], TCM is a pragmatic approach to measure the individual characteristics of SR, subsequent to WL. The use of humidity measurements under clothing is a simple monitoring technique for characterizing the sweating responses to activity and environmental challenges, and the measuring system can be wireless. Furthermore, the methodology offers a simple, practical means to develop and expand a database to evaluate the characteristics of temporal SR estimates for existing or future thermal regulatory models.

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